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13. ABSTRACT *(Maximum 200 words)*

This research covered modulation-doped field effect transistors (MODFET's) of AlInAs/GaInAs/AlInAs/InP grown by molecular beam epitaxy (MBE). These are the highest frequency transistors yet made, but generally suffer from problems.

The problem studied is that of obtaining well-behaved current vs voltage characteristics for these transistors, including reducing the anomalous "kink effect", and increasing breakdown voltage.

The most important results are the near-elimination of the "kink effect" by using reduced arsenic flux in the MBE growth, and sharply (~100:1) reduction of the gate breakdown current by using a barrier-enhancement acceptor doping plane under the gate. Near pinch-off, the drain-source voltage at breakdown was doubled. Additionally, the optimization of the fabrication technology of the mushroom (or T) shaped gates was completed for these devices, and integrated circuits for millimeter amplifiers and oscillators were designed and fabricated.

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Study of Ultra Short HFET Devices with InP Substrates

Final Report

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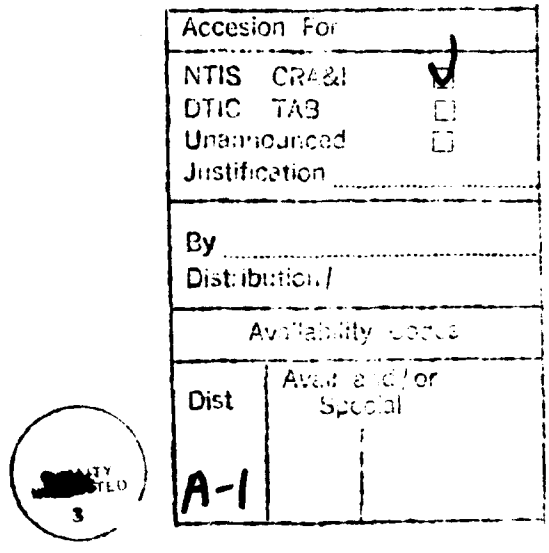

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Study of Ultra Short HFET Devices with InP

Introduction

Efforts have been geared toward improving the performance of short-gate SubstratesAlInAs/GaInAs MODFETs on InP substrates. The issues addressed and studied in this project include kink effect, current enhancement, breakdown problem, T-gate technology, and circuit applications.

A. Kink Effect

Kink effect refers to the drain current anomaly observed in the I-V characteristics of MODFETs and MESFETs that include AlInAs layers. Fig.1 shows an example of this effect. Kink effect was found to be a low-frequency phenomenon, vanishing at frequencies higher than a few megahertz(MHz). This finding, together with the observed current collapse and light sensitivity at 77 K, has led to the conclusion that the kink effect results from the presence of deep-level electron traps in the AlInAs which ionize under the high fields present in MODFETs or MESFETs under bias. Although small-signal microwave characteristics do not degrade due to the kink effect, large-signal and noise performance will be significantly affected.

It was found that if AlInAs layers are grown with the AlInAs V:III flux ratio of 5:1, instead of the standard 15:1, the kink effect is virtually eliminated. Fig.2 shows the I-V characteristics of a MODFET grown with the low As flux ratio of 5:1. This removal of the kink effect is believed to be the result of reduced unintentional impurity incorporation and redistribution during the low-As-flux growth of AlInAs.

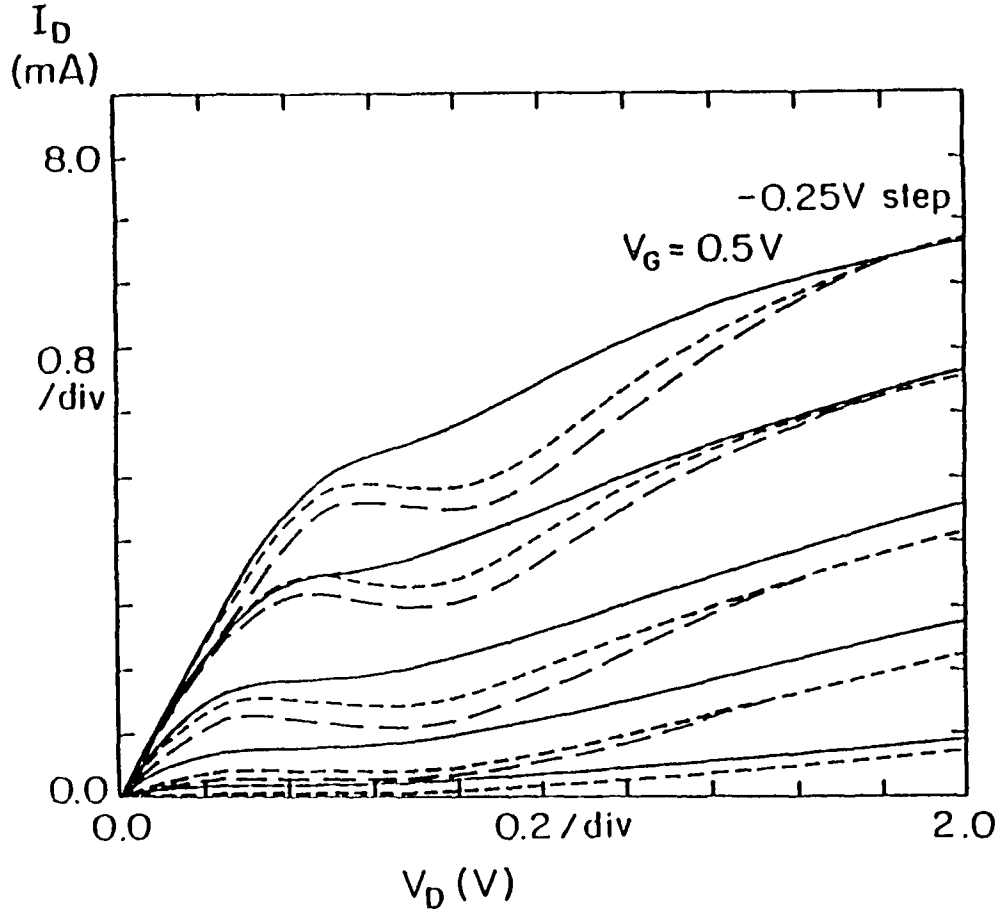

Fig. 1. Current-voltage characteristics of an AlInAs/GaInAs MODFET.

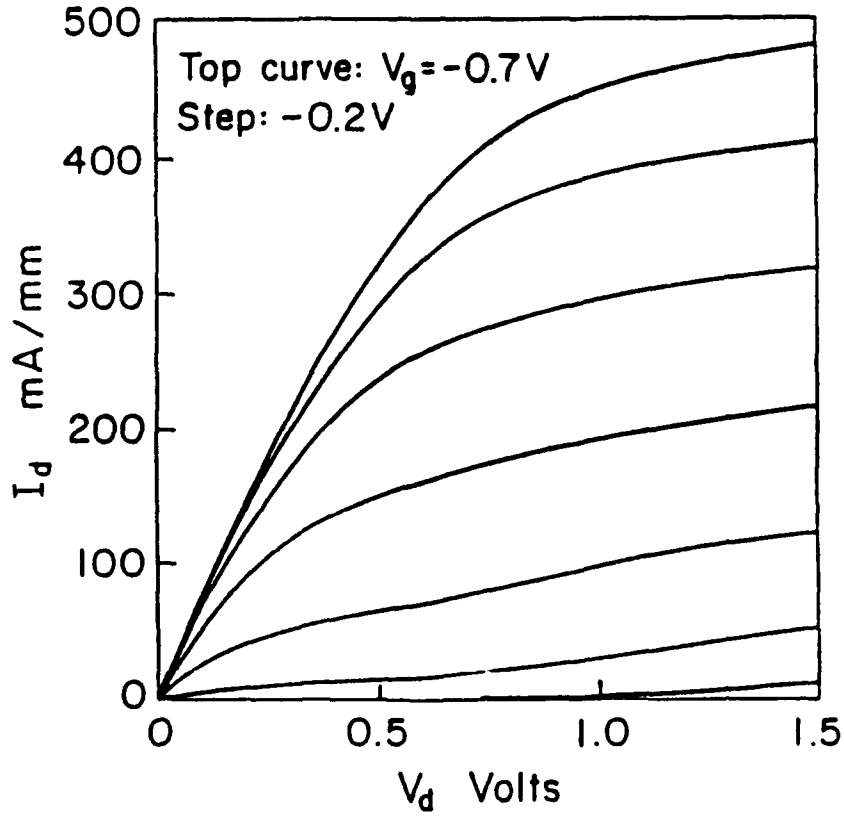

Fig. 2. Current-voltage characteristics of an AlInAs/GaInAs MODFET grown with low As flux.

B. Current Enhancement

Higher electron mobility and sheet density are expected in the strained $Al_{0.48}In_{0.52}As/Ga_{1-x}In_xAs$ ($x \geq 0.53$) MODFET structures due to the higher conduction band discontinuity and improved electron confinement. Pseudomorphic MODFETs with 6% excess indium (x=0.59) in the channel were grown and fabricated. These devices exhibit drain current in excess of 1.1 A/mm. When extra doping layer was introduced under the channel (double-doping), drain current as large as 1.8 A/mm was demonstrated.

C. T-gate Technology

The gate-length (foot-print) must be very short (less than ~0.25 μm) to reduce the electron transit time in order to achieve high performance at high frequency. However, the cross-section also becomes smaller, thereby increasing the gate resistance. This gate resistance significantly degrades the maximum available gain (MAG) at high frequency, and reduces the maximum frequency of oscillation (f_{max}). To circumvent this problem, the T-gate technology has been developed. Cambridge EBMF 10.5 has been used to produce gates with foot-print of 0.15 μm to 0.3 μm. The upper portion of these gates are ~0.5 μm wide, reducing the gate resistance from ~1500 Ω/mm (conventional triangular gate) to 300 Ω/mm or less. Fig. 3 shows an example of such T-gates.

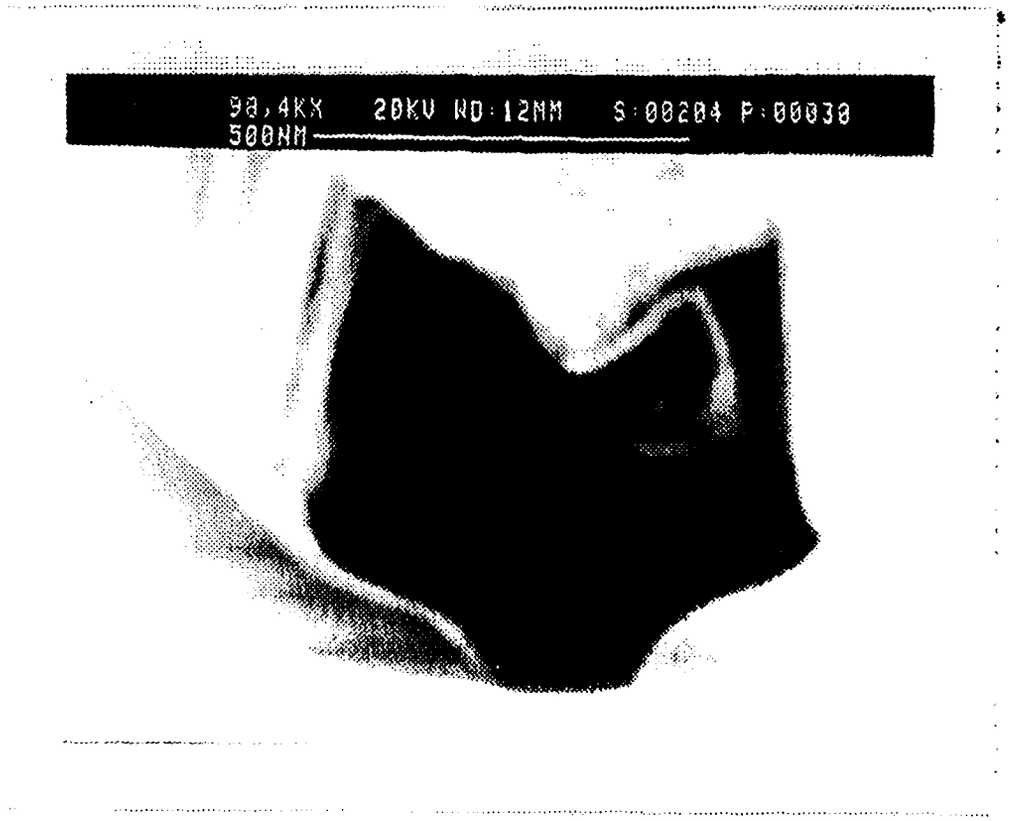

Fig. 3. T-gate with 0.15 μm footprint.

D. Gate Leakage Current

Gate leakage current due to the low Schottky barrier heights is a major problem of AlInAs/GaInAs MODFETs that leads to low breakdown voltage. Several means of reducing the leakage current have been investigated.

a. Planar Isolation

If device isolation is achieved by conventional mesa etching, gate lines come in contact with the two-dimensional electron-gas (2DEG). Since the Schottky barrier height for metal on GaInAs is very low (~0.25 eV), this contact could lead to leakage current. To eliminate this possibility, ion-bombardment damaging was employed for electrical isolation between devices. Boron bombardment with a dose from $7x10^{12}$ to $1x10^{13}$ cm^{-2}, and energy from 35 to 40 KeV yielded good device isolation. Later, Ar bombardment with a dose of $5x10^{12}$ cm^{-2} and energy of 80 KeV was found to be equally effective.

b. Barrier-enhancement Layer

To reduce the gate leakage current, especially at and beyond the cutoff bias conditions, an acceptor plane was suggested just under the gate region, but above a donor plane, to create a dipole of opposite sheet charges. The donor plane is used to supply electrons to form the 2DEG in the channel. The acceptor plane is used to enhance the effective Schottky barrier height. With a proper design, barrier height can be enhanced without seriously affecting the 2DEG density. Fig. 4 shows the potential profile of the conduction band in the channel region with such an atomic planar-doped dipole with equal donor and acceptor ion sheet densities. The top cap is

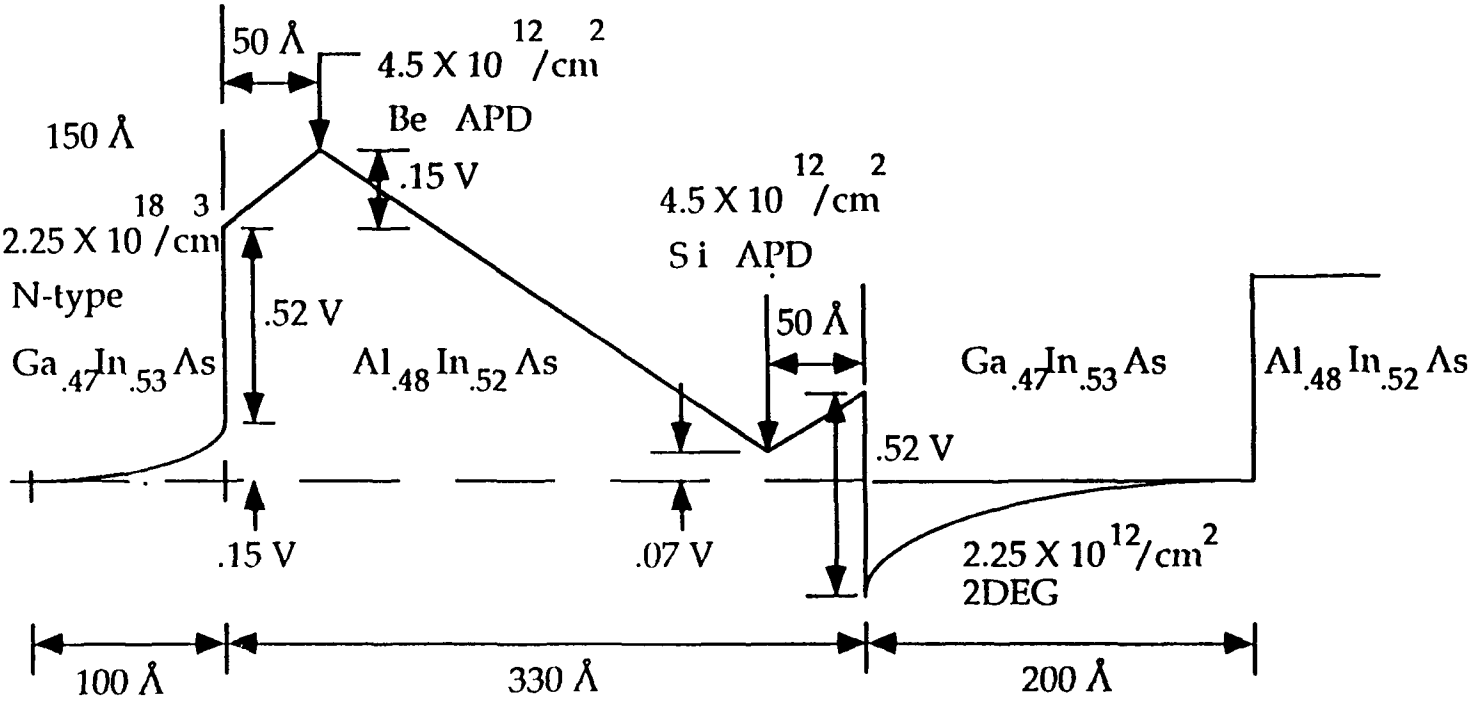

Fig. 4. Conduction band potential profile of barrier-enhanced MODFET structure along channel.

required to have enough donors to be depleted from underneath, in order to terminate the electric fields on the top side of the acceptor plane as shown. This profile is drawn to scale for a design allowing 2.25×10^{12} cm^{-2} in the 2DEG. The 2DEG density can be varied by changing the doping density of the donor plane. Fig. 5 shows the conduction band profile under the gate at cutoff gate bias of -1.5 V for the structure shown in Fig. 4. As can be seen, there is an additional 50 Å of constant-height barrier (~0.52 V) between the gate metal and the potential region descending sharply, compared to the conventional, non-barrier-enhancing design. Simple quantum-mechanical calculations predict four orders if nagbutyde (10^{-4}) reduction in tunneling current from the electrons at the Fermi level in the gate metal. Therefore, this could be a powerful method of reducing the gate leakage current at and above the channel cutoff conditions where tunneling is the dominant breakdown mechanism. Experiments revealed, however, that atomic planar-doping of the acceptor may not be optimal due to the fast diffusion of the Be. Therefore, thin, uniformly-doped Be layer was used instead to accomplish the same result.

To demonstrate the effectiveness of this concept, Schottky diodes were first fabricated on AlInAs layers which incorporated 100 Å of p^+ barrier-enhancement layers doped with Be to 6×10^{18} cm^{-3}. These diodes showed 0.4 V increase in forward-bias turn-on voltage, and 50 to 100 times reduction in reverse-bias leakage current compared to diodes without the p^+ layers. Fig. 6 shows these results.

MODFETs with 0.3 µm gate were fabricated on AlInAs/GaInAs layers incorporation 60 Å of p^+ barrier-enhancement layer doped with Be to 1×10^{19} cm^{-3}. Typical 50 µm-wide MODFETs exhibited f_T of 70 GHz, f_{max} of 130 GHz, peak g_m of 450 mS/mm, g_o at peak g_m of 25 mS/mm, g_m/g_o

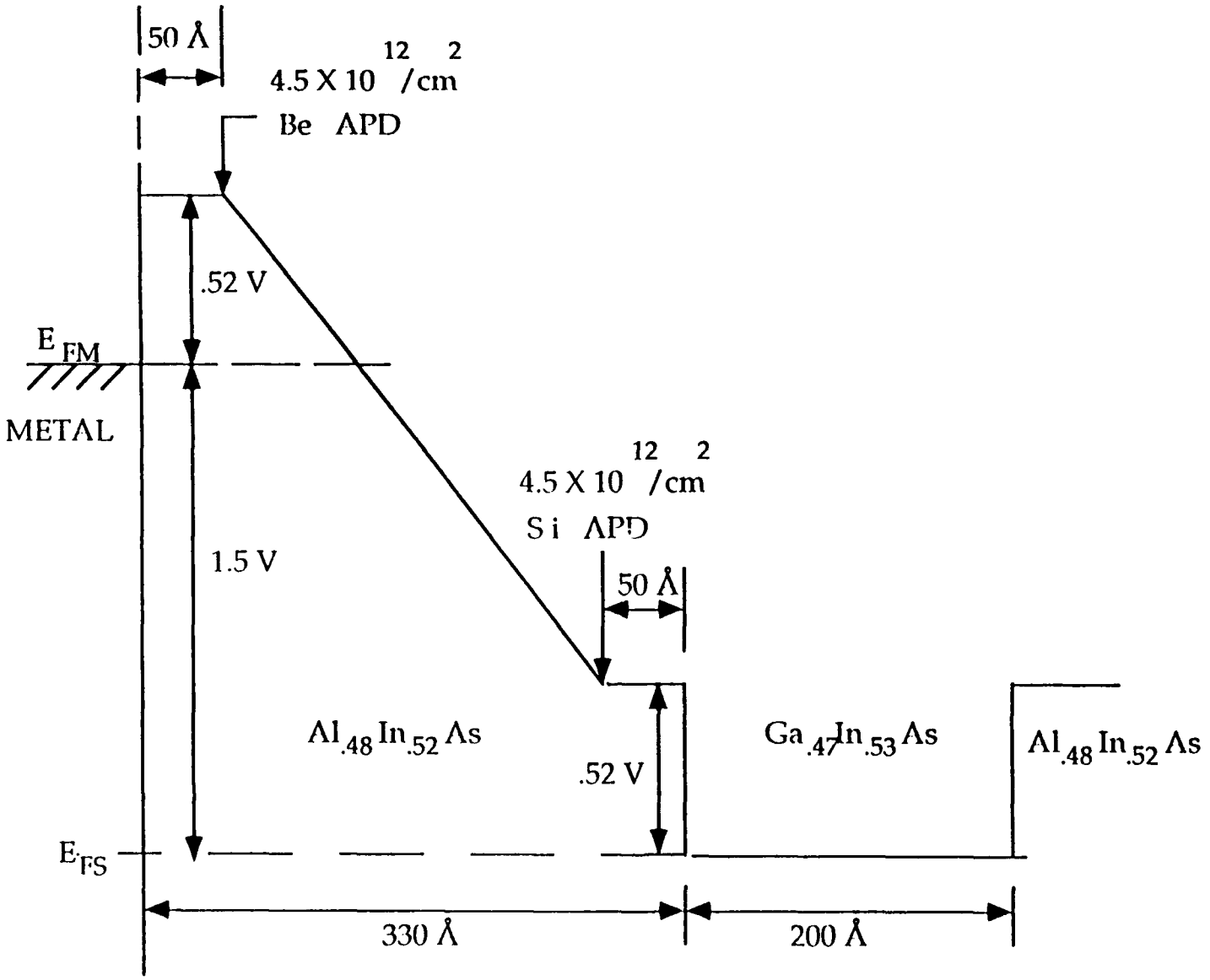

Fig. 5. Potential profile of barrier-enhanced MODFET structure under gate at cutoff.

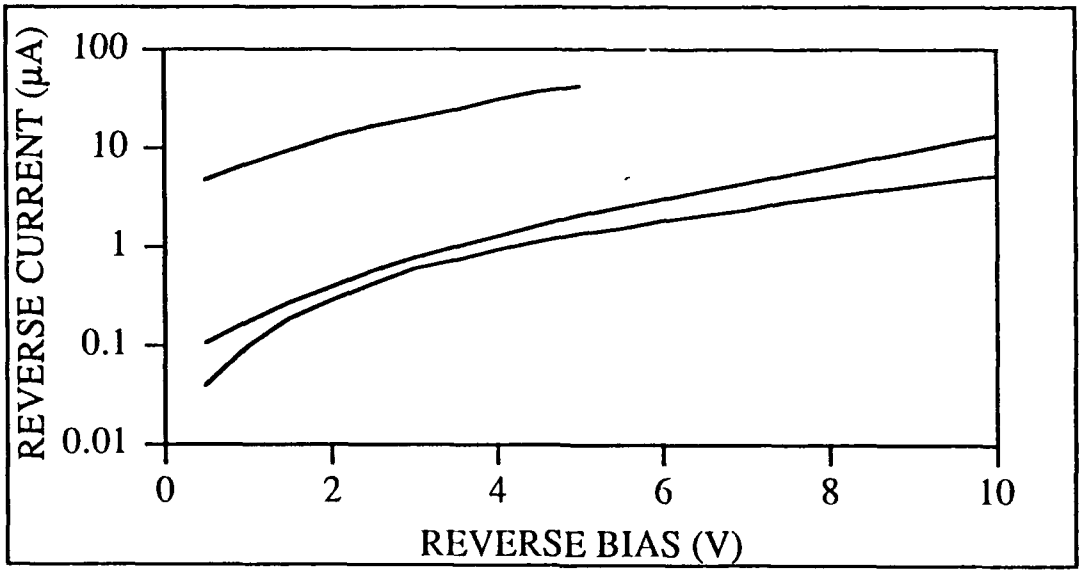

Fig.6. Effect of barrier-enhancement layers on diode leakage current.

ratio of 18, maximum current of 700 mA/mm, and drain-source breakdown voltage in excess of 7 V near pinchoff (gate-bias of -2 V). The I-V characteristic of this device is shown in Fig. 7. These results demonstrate the potential of barrier-enhanced AlInAs/GaInAs MODFETs in microwave power applications.

E. Circuit Applications

Short-gate AlInAs/GaInAs MODFETs lattice-matched on InP, together with planar Schottky-barrier mixer diodes, are being developed for millimeter-wave, low-noise receiver applications. Amplifiers and oscillators in the 20-60 GHz range will serve as test vehicles. Electron-beam lithography will be used throughout the process to accommodate the frequent modification of the design during the initial development phase.

a. Simulations

Simulations have been performed to determine the optimum material structure, using a Poisson's equation solver. Circuit simulations have been performed with theTouchStone program to predict the power gain of the amplifiers in the frequency range up to 300 GHz. The predicted upper limit to the practically achievable gain is about 15 dB at 100 GHz, and 12 dB at 200 GHz, with 0.1 μm gates. Simulations also predict that, below about 100 GHz, only transconductance g_m, gate-source capacitance C_{gs}, gate-drain capacitance C_{gd}, and source resistance R_s affect the gain, while above 100 GHz, gate resistance R_g, output conductance g_{ds}, and drain resistance R_d also play important roles.

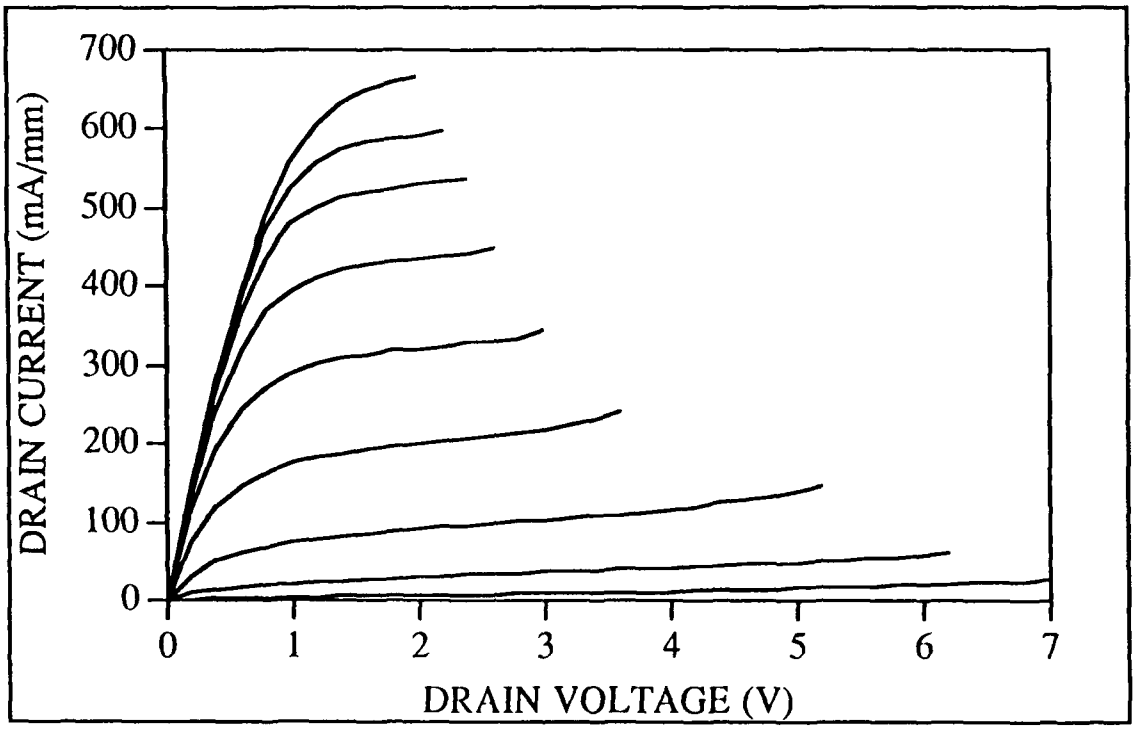

Fig. 7. Current-voltage characteristics of an AlInAs/GaInAs MODFET with barrier-enhancement layers.

b. Circuit Design and Process Development

A test chip containing both T-type and π-type MODFETs (Figs. 8 and 9), planar mixer diodes (Fig. 10), oscillators (Fig. 11), and amplifiers (Fig. 12), has been designed for the 20-60 GHz range.

Low-resistance T-gates with footprint between 0.15-0.3 μm have been developed as mentioned previously.

An air-bridge technology which is realized entirely by electron-beam lithography has been developed to facilitate the initial development phase of integrated circuits.

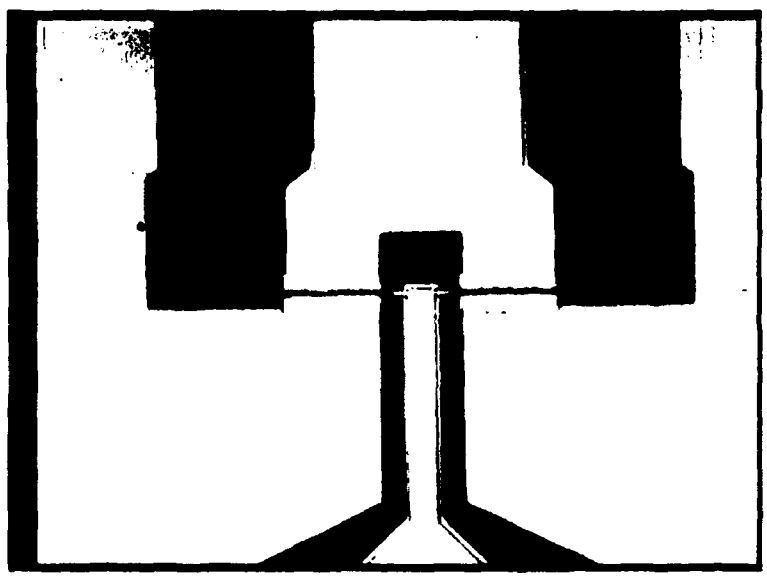

Fig.8. Detail of 2 x 25 μm T-MODFET.

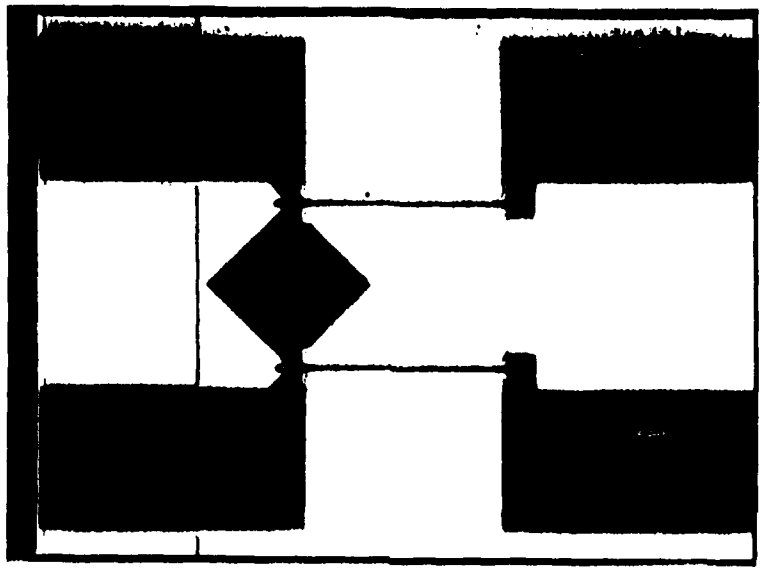

Fig. 9. Detail of 2 x 50 μm π-MODFET.

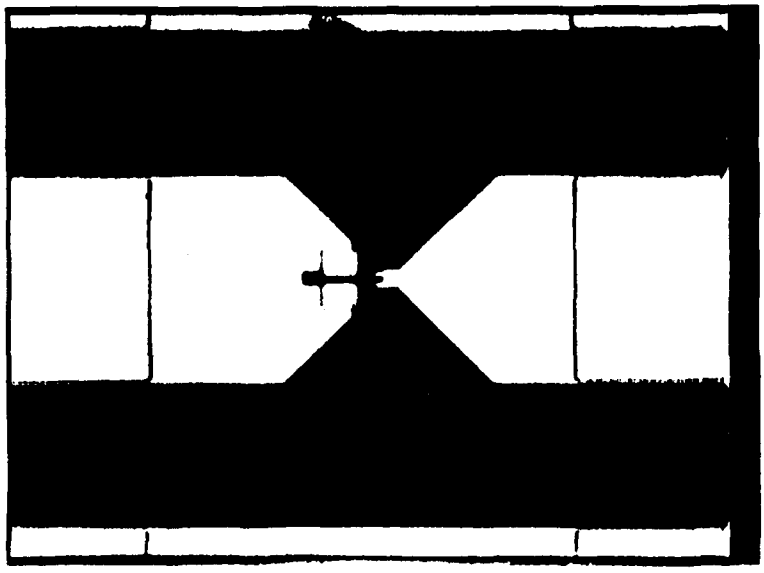

Fig. 10. Detail of 10 μm mixer diode.

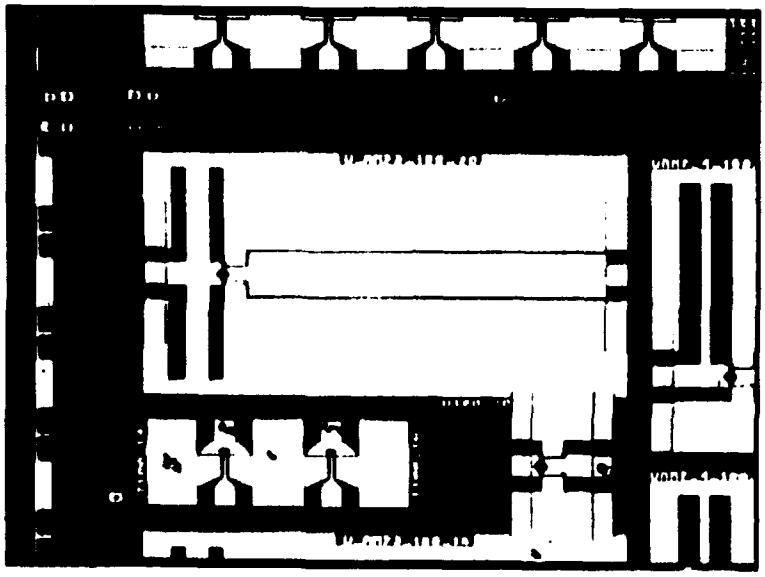

Fig. 11. Coplanar 60 GHz amplifier.

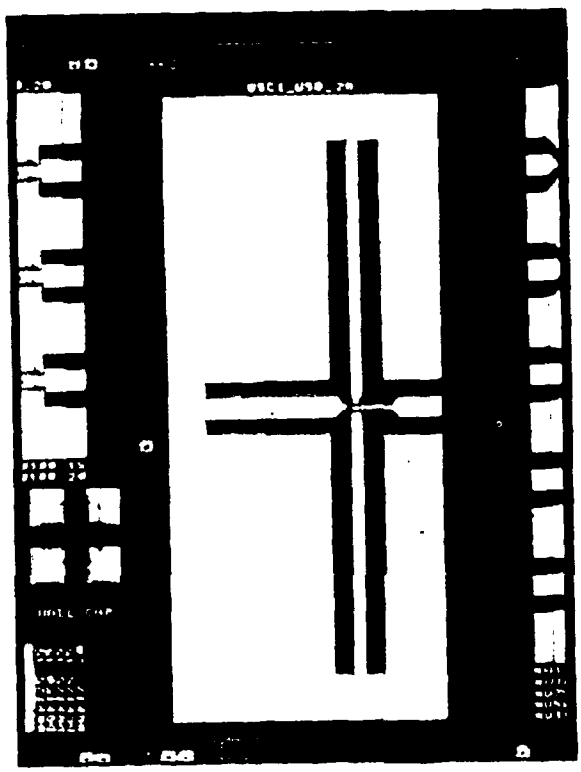

Fig. 12. Coplanar 60 GHz Ocillator.

Publications and Presentations reported on Army Contract DAAL03-89-K-0006

"I/V Anomality and Device Performance of Submicrometre-Gate $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ HEMT", J.B. Kuang, P.J. Tasker, Y.K. Chen, G.W. Wang, L.F. Eastman, O.A. Aina, H. Hier, and A. Fathimulla, Electronics Letters **24** (25) 1571-1572 (Dec. 8, 1988).

"Kink Effect in Submicrometer-Gate MBE-Grown InAlAs/InGaAs/InAlAs Heterojunction MESFET's", J.B. Kuang, P.J. Tasker, G.W. Wang, Y.K. Chen, L.F. Eastman, O.A. Aina, H. Hier, and A. Fathimulla, IEEE Electron Device Lett., **9** (12) 630-632 (Dec. 1988).

"Submicron-Gate $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ Heterojunction Metal-Semiconductor Field-Effect Transistors Grown by Molecular Beam Epitaxy", J.B. Kuang, P.J. Tasker, Y.K. Chen, G.W. Wang, L.F. Eastman, O.A. Aina, H. Hier, and A. Fathimulla, Appl. Phys. Lett. **54** (12) 1136-1138 (Mar. 20, 1989).

"DC and rf Measurements of the Output Conductance in 0.2 mm Gate Length AlInAs/GaInAs/InP MODFETs", L.F. Palmateer, P.J., Tasker, W.J. Schaff, L.D. Nguyen, and L.F. Eastman, Appl. Phys. Lett., **54** 2139-2141, (May 22, 1989).

"Comparison of Vacuum and Semiconductor Field Effect Transistor Performance Limits", L.F. Eastman, 2nd International Conference on Vacuum Microelectronics, Bath, England, (July 24-26, 1989); IOP Conf Ser. No. 99, Section 7 , 189-194 (1989).

"A Study of Submicron-gate InP-based MODFET's", J.B. Kuang, P.J. Tasker, and L.F. Eastman,Prosus presentation (Internal) (Oct. 9-10, 1989).

Low Frequency and Microwave Characterization of Submicron-gate $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ Heterojunction Metal-Semiconductor Field-Effect Transistors Grown by Molecular-Beam Epitaxy", J.B. Kuang, P.J. Tasker, S. Ratanaphanyarat, W.J. Schaff, L.F. Eastman, G. W. Wang, Y.K. Chen, O.A.Aina, H. Hier, and A. Fathimulla, J. Appl. Phys., **66** (12) 6168-6174 (15 Dec. 1989).

"Progress in Microwave and Millimeter Wave Transistors", L.F. Eastman, IEEE Section, GE, Syracuse,NY (Feb. 14, 1990)

"Self-aligned RTO Finger Structure for High Cut-off Frequency and Device Integration", X.J. Song, J.B. Kuang, W.J. Schaff, P.J. Tasker, L.F. Eastman and K. Yamasaki, SPIE Conf. on 'High Speed Electronics and Device Scaling' , San Diego, CA (Mar. 17-21, 1990) Vol. **1288**, 136-144.

Cryogenic Noise Performance of OMVPE-Grown InGaAs/InP MODFET's", K. B. Kuang, Y.K. Chen, M. A. Chin, R.A. Logan, T. Tanbun-Ek, and L.F. Eastman, SPIE Conf. on 'High Speed Electronics and Device Scaling, San Diego, Ca. (Mar. 17-21, 1990), Vol. **1288**, 258-268.

"Scaling of Parasitics in Millimeter Wave MODFETs", B. Hughes and P.J. Tasker, SPIE Conf. on 'High Speed Electronics and Device Scaling', San Diego, CA (Mar. 17-21, 1990) Vol. **1288,** 227-237.

"Research of High Frequency Devices at Cornell", L. F. Eastman, Invited seminar at Hughes Research, Malibu,CA (March 20, 1990).

"Progress in High Frequency Heterojunction Field Effect Transistors", L. F. Eastman, (ESSDERC 90) *20th European Solid* State Device Research Conference, (Sept. 10-13, 1990), Nottingham, England, Inst. Physics (Adam Higler) edited by W. Eccleston and P.J. Rosser, p. 619-624 .

"High Current Lattice-Strained $In_{0.59}Ga_{0.41}As/In_{0.52}Al_{0.48}As$ Modulation-Doped Field-Effect Transistors Grown by Molecular Beam Epitaxy", J.B. Kuang, Y.K. Chen, D. Sivco, A.Y. Cho and L.F. Eastman, Appl. Phys. Lett., **57**, 1784-1786 (Oct. 22,1990).

"Novel Structures for High Speed/High Frequency Optoelectronic Devices and Integrated Circuits", L.F. Eastman, SPIE Int. Conf. on Physical Concepts of Materials for Novel Optoelectronic Device Applications, Aachen Germany (Oct. 29 - Nov. 2, 1990). (SPIE Optical Engineering Press, Bellingham, WA) 41-56.

"The In-plane Effective Mass in Strained-Layer Quantum Wells", B.K. Ridley, J. Appl. Phys, **68** (9) 4667-4673 (1 Nov. 1990).

"Study of Means of Increasing Power Levels with Al,InAs/GaInAs/InP MODFET's", L.F. Eastman, W.J. Schaff, J.B. Kuang, H. Park, P. Mandeville, and W. Haydl, Engineering Foundation 'Advanced Heterostructure Transistors', Kona . Hawaii (Dec. 3-8, 1990).

"Millimeterwave Coplanar Transmission Lines on Gallium Arsenide, Indium Phosphide and Quartz with Finite Metalization Thickness", W.H. Haydl, T. Kitazawa,J. Braunstein, R. Bosch, M. Schlechtweg, IEEE Intl. MTT-S Microwave Symp. Boston, MA. (June 11-14, 1991), Digest to be published.

Advanced Degrees

"DC and RF Characterization of GaInAs/AlInAs/InPh Modulation Doped Field Effect Transistors for Millimeter Wave Device Applications", Lauren F. Palmateer (Ph.D.) May 1989.

"Submicrometer-Gate Indium Phosphide-Based Field-Effect Transistors for High-Frequency Applications", Jente B. Kuang (Ph.D.) August 1990.

in progress --- H. Park (Ph.D.) May 1992.

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